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THE PERCEPTUAL INTERACTION OF GRAPHICAL ATTRIBUTES IN THIRTEEN BIVARIATE DISPLAYS

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Thirteen bivariate graphical displays were used to perform the speeded classification tasks necessary to diagnose dimensional integrality, configurality, and separability. The nine classification tasks were performed by a different group of nine subjects for each of the graphs. Results from 9 of the 13 graphs clearly fit the pattern indicative of integrality. Instead, graphs varied on a continuum from highly configural to separable displays. A principal components analysis was used to derive a composite measure of configurality, and this measure was found to be correlated with the homogeneity of the various graphs. Greater homogeneity among graphical attributes was associated with higher performance-based configurality scores.

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CONTENTS

INTRODUCTION 3

DIMENSIONAL INTEGRALITY 4

DIMENSIONAL CONFIGURALITY 5

OBJECT PROCESSING 7

EXPERIMENTAL OVERVIEW AND RATIONALE 7

Methods 8
Results and Discussion 16

DISCUSSION

Integrality Versus Configurality 32
The Measurement of Configurality 33
Homogeneity of Physical Attributes 34
Object Displays 35

CONCLUSIONS 35

REFERENCES 37

FIGURES

1. Sample of 13 Bivariate Graphs, Each of Which was Used by an Independent Group of Subjects to Perform Nine Speeded Classification Tasks 9
2. Nine Speeded Classification Tasks as Performed With the Dot Charts 12
3. Component Scores for the First (Horizontal Axis) and Second (Vertical Axis) Principal Components for Each of the 13 Graphs 31

TABLES

1. Range and Median Correlation Between Reaction Time and Percentage Correct for Each of the 13 Graphs 15
2. Summary Variable Used in the Principal Components Analysis of Task Performance Across Graphs 16
3. Mean Reaction Times (msec) and Percentage Correct for Each of the Nine Classification Tasks Performed With the Line Graphs and Dot Charts 17
4. Mean Reaction Times (msec) and Percentage Correct for Each of the Nine Classification Tasks Performed With the Rectangles and Glyphs 19
5. Mean Reaction Times (msec) and Percentage Correct for Each of the Nine Classification Tasks Performed With the Folding Fans, Fans, and Meters 22

6. Mean Reaction Times (msec) and Percentage Correct for Each of the Nine Classification Tasks Performed With the Colorbars 24

7. Mean Reaction Times (msec) and Percentage Correct for Each of the Nine Classification Tasks Performed With the Variable-Color Whiskers and the Colorbar-Meters 25

8. Mean Reaction Times (msec) and Percentage Correct for Each of the Nine Classification Tasks Performed With the Variable-Length Whiskers, Trees, and Dot-Meters 28

9. Unrotated Factor Pattern for the First Two Principal Components Derived From the Correlation Matrix of the Seven Summary Performance Measures 30

THE PERCEPTUAL INTERACTION OF GRAPHICAL ATTRIBUTES IN THIRTEEN BIVARIATE DISPLAYS

INTRODUCTION

The success with which we are able to extract information from graphical displays seems to vary greatly from graph to graph, and from situation to situation. The best graphs allow us to use information from very complex, multivariate data sets, information that would be overwhelming or even totally incomprehensible if presented as a tabular array of numbers. However, all too often, our graphs fall short of their potential usefulness. It has been the joint task of display designers and psychologists to determine what factors influence the success or failure of graphical communication.

The label "comparative graphics" has been applied by DeSanctis (1984) to the study of graphical communication. As the name implies, most research has involved the comparison of several graphical formats in order to rank the efficiency with which they can be used. However, in choosing their stimulus sets and discussing their results, various researchers have emphasized several different design features that may each contribute to graphical efficacy. For example, Wrightstone (1936) emphasized the distinction between pictorial graphs (i.e., pictograms) and nonpictorial or abstract geometric graphs such as bar graphs and line charts. In other cases, the user's familiarity with the graphs has also been emphasized (Vernon, 1952), an opinion still frequently voiced (Chernoff, 1973; Jacob, Egeth, & Bevan, 1976). Recently, Tufte (1983) has emphasized the importance of maximizing the "data-ink ratio" in graphs. He suggests that the best graphs are those that present the most data with the least ink. To accomplish this, display designers should avoid redundancies, stylistic flourishes, and any other unnecessary details.

Applied experimental psychologists have a long tradition of studying the accuracy of identification and discrimination of stimulus levels along continuous physical dimensions, and this information is routinely presented in discussions of display design (e.g., Hutchingson, 1981; McCormick & Sanders, 1982). This tradition has recently been systematically applied to graphical displays by Cleveland and coworkers (Cleveland, 1985; Cleveland, Harris, & McGill, 1983; Cleveland & McGill, 1984; Cleveland & McGill, 1985) who have provided a list of "basic graphical elements" ordered in terms of the accuracy with which subjects can use them to make relative magnitude judgments.

This report emphasizes an emerging trend in comparative graphics, a trend that shifts attention from the perception of individual physical dimensions to the perceptual interactions associated with combinations of such dimensions. At the heart of this approach is the belief that individual elements in some multi-element graphs are not processed by the observer in an analytical, element-by-element fashion. Instead, pairings of elements that are manipulated independently by the display designer (or perceptual researcher) may sometimes be viewed as unitary or dependent by the graph's user. This unitary or holistic processing should have varying consequences for performance in graphical tasks, facilitating performance in some cases and proving detrimental in others. In light of the increasing awareness that the usefulness of any particular graphical

format is task-dependent (see Carswell & Wickens, 1988, and DeSanctis, 1984, for reviews), research of the factors influencing holistic processing (which may in turn interact with task demands) seems particularly appropriate. To date, three concepts relevant to holistic processing have been applied to graphical design: dimensional integrality, dimensional configurality, and object processing.

DIMENSIONAL INTEGRALITY

As Pachella, Somers, and Hardzinski (1981) have observed, the term integrality has a variety of meanings, both intuitive and technical. The intuitive meaning is relatively straightforward, referring to the subjective unity of the various attributes of a multi-attribute stimulus. For example, the position of a single point on a graph seems relatively unitary, even though we know that the position can be broken down into horizontal and vertical positions, and that these two attributes are frequently used in the design of graphs to represent values of two distinct variables (e.g., a point in a scattergram). Still, it is relatively difficult to focus attention solely on horizontal position while altogether ignoring the point's vertical position. Intuitively, horizontal and vertical positions are integral.

Technically, dimensional integrality is a means of classifying physical dimensions based on the manner in which they interact perceptually. Using the example of vertical and horizontal positions once again, we would like to know if these attributes are coded separately by the human information processing system. Alternatively, is a two-dimensional position coded and processed directly as a "fundamental unit" of perception? Two physical attributes that correspond to a single perceptual code are integral, while two physical attributes that are each associated with distinct perceptual codes are separable. Treisman (1986), in a review of the evidence for analytical processing of stimulus properties, has suggested that subjective impressions of the unitariness of perceptual experience may reflect late stages of perceptual processing and may be quite misleading with regard to earlier stages. To address dimensional interactions in these earlier stages, researchers have frequently relied on latency data obtained in speeded classification tasks.

Garner and coworkers (Garner, 1970, 1974, 1976; Garner & Felfoldy, 1970) have most systematically delineated the performance outcomes that result when physical dimensions are perceptually integral. Garner reasoned that in performing a speeded classification task with two integral dimensions, filtering decrements should be observed. That is, classification of a target dimension should be disrupted when a to-be-ignored dimension is simultaneously varied in an orthogonal manner. However, if this extraneous dimension is redundantly varied, classification performance should be facilitated, producing a redundancy gain. If the dimensions are separable, the classification of one dimension should not be affected by the variation of the other dimension. Thus, the two dimensions do not interact to influence performance. Garner and Felfoldy (1970) obtained the integral pattern of results, filtering decrements with redundancy gains for hue and saturation of color chips. They found the separable pattern of results for circle size and orientation of a radius.

Reasoning that if speeded classification performance could reflect dimensional interactions such as integrality, students of comparative graphics

have attempted to use the integral or separable classification to predict graphical efficacy in a variety of tasks. Jacob et al. (1976) used "integral displays" (i.e., graphs composed of integral dimensions) to support performance in identification tasks. Goldsmith and Schvaneveldt (1984) and Goettl, Kramer, and Wickens (1986) compared integral and separable graphs for a multicue judgment task. Studies of failure detection and diagnosis in process control scenarios have also been performed using both integral and separable displays (Carswell & Wickens, 1987; Casey & Wickens, 1986; Jones, Wickens, & Deutsch, 1989; Petersen, Banks, & Gertman, 1981). As a general rule, it seems that integral displays are related to superior performance only when subjects must integrate several variables to reach a decision. However, separable displays seem to better support performance in tasks requiring information localization or performance of several independent tasks simultaneously (see Carswell & Wickens, 1988, for a review).

However, the labeling of graphs as integral or separable for purposes of comparative graphics research has been largely based on intuitive definitions. In none of the studies have the standard diagnostics of speeded classification been used to classify or rank the graphs in terms of their integrality, thus limiting our ability to relate these results to specific theoretical conceptions of attribute interaction. Some of the authors have even questioned whether any of their graphical elements were truly integral (Carswell & Wickens, 1987; Jacob et al., 1976). But the most disturbing results have come from those tasks which should most strongly benefit from the processing consequences of integrality, those tasks in which variables displayed by the graph were intercorrelated (Casey & Wickens, 1986; Jones, Wickens, & Deutsch, 1989). These studies have found integral graphics to be less useful for monitoring correlated information, even though one of the major diagnostics of integral dimensions is generally considered to be redundancy gain in classification tasks. Thus, the usefulness of the integrality concept for describing graphical displays has been brought into question.

DIMENSIONAL CONFIGURALITY

In addition to dimensional integrality, the concept of configurality has been proposed as a type of dimensional interaction. Rather than two or more physical dimensions forming a single perceptual dimension, as with integral dimensions, configural dimensions maintain separate codes perceptually. However, in addition to these separate properties, new relational or "emergent" properties are also coded (Garner, 1974, 1978, 1981; Pomerantz, 1981; Pomerantz & Garner, 1973; Pomerantz, Sager, & Stoever, 1977). Such properties as figural symmetry, closure, and similarity are all examples of such emergent features. Researchers have proposed that configurality of graphical elements rather than integrality may be useful for describing the holistic processing benefits that accrue to some graphs (e.g., Barnett & Wickens, 1988; Buttigieg, Sanderson, & Flach, 1988; Coury & Purcell, 1988; Jacob et al., 1976).

Unlike dimensional integrality, configurality does not have widely agreed upon performance-based diagnostics. However, the measurement of condensation performance in speeded classification is sometimes used (Pomerantz & Schwaitzberg, 1975). Condensation involves using each of several physical dimensions to determine the appropriate category membership of a stimulus. Thus,

category membership is based on the particular conjunction of values on each of two dimensions (e.g., color and size) so that classification based on only one of these attributes is insufficient to generate correct responses. Pomerantz (1981) has referred to this task as a measure of divided attention since two physical dimensions must both receive some processing. However, if an emergent feature is present, the classification decision can often be made solely on the basis of that feature, and thus is made more quickly than if each parent dimension were being processed sequentially.

In addition to relatively efficient condensation performance, perhaps attributable to the presence of a salient emergent feature, configural dimensions are generally believed to impair filtering performance (Pomerantz, 1981; Pomerantz & Garner, 1973). This failure of focused attention is often attributed to a misallocation of attention rather than to a total inseparability of the component parts, as is generally assumed with integrality. Also in contrast with dimensional integrality, configurality is not related to redundancy gain; classification performance when the two attributes configure is no faster than classification of each attribute alone. Thus, the convergence of efficient condensation, poor filtering, and no clear redundancy gain has been used to diagnose configural dimensions.

Pomerantz and Pristach (1986) have suggested an additional diagnostic: discrepancies in classification performance of correlated dimensions may indicate configurality. Usually, in any speeded classification battery, two different redundancy conditions are studied. There may be a positive correlation condition, for example, when large values on one dimension are paired with large values on the other, and this stimulus is classified against one containing smaller values on both dimensions. Alternatively, a negative correlation between the dimensions may be used to define the two stimulus classifications. For example, the positive correlation between height and width of rectangles produces stimuli that vary in terms of size, while a negative correlation between height and width produces stimuli that may be discriminated in terms of shape. Weintraub (1971) found that subjects could identify rectangles on the basis of shape more readily than they could identify rectangles that differed in size. Thus, differences or asymmetries in tasks used to measure redundancy gain should not be surprising if salient emergent features such as size or shape are available for one or both tasks, even when the differences between the parent dimensions are identical in both cases. Thus, asymmetries in tasks requiring classification of two different subsets of correlated dimensions may be a further indication that emergent features are being used by subjects.

Finally, a further diagnostic is implied by Garner's (1974) definition of configural dimensions as "optionally separable." This would suggest that there might be a great deal of variation among subjects in terms of whether a particular emergent feature exerted its influence on performance. Thus, some subjects might be able (or prefer) to focus on the parent dimensions of a stimulus, thereby showing a separable pattern of performance, while other subjects, attending to the more global emergent feature, would show a disruption of focused attention to the parent dimensions. Greater variation in filtering performance during speeded classification would be expected for configural dimensions compared to either mandatory separable or integral dimensions.

OBJECT PROCESSING

Object displays are graphs that use the several physical dimensions of a single object to display several quantitative variables (see Wickens, 1987, for a review). These displays are contrasted with multi-object displays in which dimensions of several separate objects are used to provide information about several different variables. An example of an object display would be the use of the height and width of a rectangle to represent the values of two variables, while an example of a multi-object display would be the use of the height of two separate rectangles (a bar graph) to represent the same information.

Object displays represent a somewhat more general category of holistic processing characteristics, subsuming aspects of both integrality and configurality described earlier. For example, Garner (1976) has argued that attributes of two distinct objects are almost surely separable. Being attributes of a single object, on the other hand, is likely to be a necessary if not sufficient condition for integrality. Further, Pomerantz and Schwaitzberg (1975) have demonstrated that configurality effects are stronger with increases in spatial proximity between parent dimensions. Since parts of an object are usually located proximally, there may be an increased chance of configurality effects among object displays. Object displays, then, may benefit (or suffer) from the holistic processing resulting from either integrality or configurality to a greater extent than the more traditional multi-object formats.

In addition to these specific contributions of integrality and configurality, the processing of objects may have consequences for their separable component dimensions. Kahneman (Kahneman & Henik, 1981; Treisman, Kahneman, & Burkell, 1983), in his "object file" model of attention, has suggested that processing of the separable attributes of an object proceeds in parallel and is without cost to resources at the perceptual registration stage. Allocating attention to one attribute of an object automatically invokes concurrent processing of the other attributes. Kramer, Wickens, and Donchin (1985), for example, have found that increasing the demand for processing one attribute of a single object display facilitates the processing of the other attributes. The benefits of object processing and object displays seem promising; however, research on the utility of object displays for graphical communication awaits preliminary research that can (a) identify which aspects of common object displays are most likely to be separable (i.e., neither integral nor configural), and will (b) address the concern voiced by some authors (e.g., Duncan, 1984) regarding the variety of stimuli that different researchers have classified as "single objects."

EXPERIMENTAL OVERVIEW AND RATIONALE

Several important issues surround the potential applicability of the integrality, configurality, and object-processing concepts to graphic design. One of the chief issues concerns the representativeness of integrality as a characterization of attribute interactions among common graphical elements. Is integrality or, alternatively, configurality, more common among attributes that are not clearly separable? To address this issue, a sample of 13 bivariate graphs was selected for the current study. Each of these graphs was used by subjects to perform the set of speeded classification tasks traditionally used to

assess integrality. In addition, a condensation task was used to diagnose configural interactions. Thus, the overall incidence of integrality, separability, and configurality among this sample was assessed.

An additional objective of the present research focuses on the performance outcomes predicted for configural dimensions by different investigators. A recent objection to the utility of the integrality concept has been the lack of convergence among the several performance outcomes purported to diagnose such dimensional interaction (Cheng & Pachella, 1984). If configurality is to prove to be a useful concept for research in comparative graphics, it would be reasonable to subject its proposed diagnostics to a similar analysis. Thus, we should ask whether those graphs associated with high condensation efficiency are also associated with large filtering decrements, asymmetric performance in different redundancy tasks, and large between-subject variation in filtering performance. Moreover, are these factors independent of overall redundancy gain? These interrelations were assessed in a principal components analysis of results from the traditional speeded classification tasks.

As a final objective, the relationship between the "object display" design concept, integrality, and configurality was addressed. Thus, we were able to test the assumption that integral and configural interactions between dimensions are more likely to occur when those dimensions are part of a single perceptual object.

Methods

Subjects

One hundred seventeen subjects were recruited for the study, with nine subjects performing the speeded classification battery for each of the 13 graphs. The ratio of males to females or vice versa was never greater than two to one for any of the groups. Subjects were students in an Introductory Psychology course offered at the University of Illinois and were given class credit for participation. All subjects reported having normal or corrected-to-normal vision. Any subject reporting color blindness was screened from the study. Eighty-three percent of the subjects were between 18 and 21 years of age. The remainder ranged from 17 to 29 years.

Graphical Displays

Since one of the objectives of the present study was to gain information about the incidence of configurality and integrality among common graphical displays, the rationale for choosing the 13 graphs is of critical importance. The choice of these graphs, shown in Figure 1, was based on four criteria. First, three physical dimensions used to construct many common graphs were chosen as the building blocks for all 13 graphs. These dimensions--position (or linear extent), orientation, and color--were chosen from Cleveland's (1985) summary of "basic graphical elements." A second objective was to manipulate the likelihood of including both integral and separable displays. Accordingly, both single and multi-object displays were included. Third, we manipulated the likelihood of including both configural and nonconfigural dimensions by creating

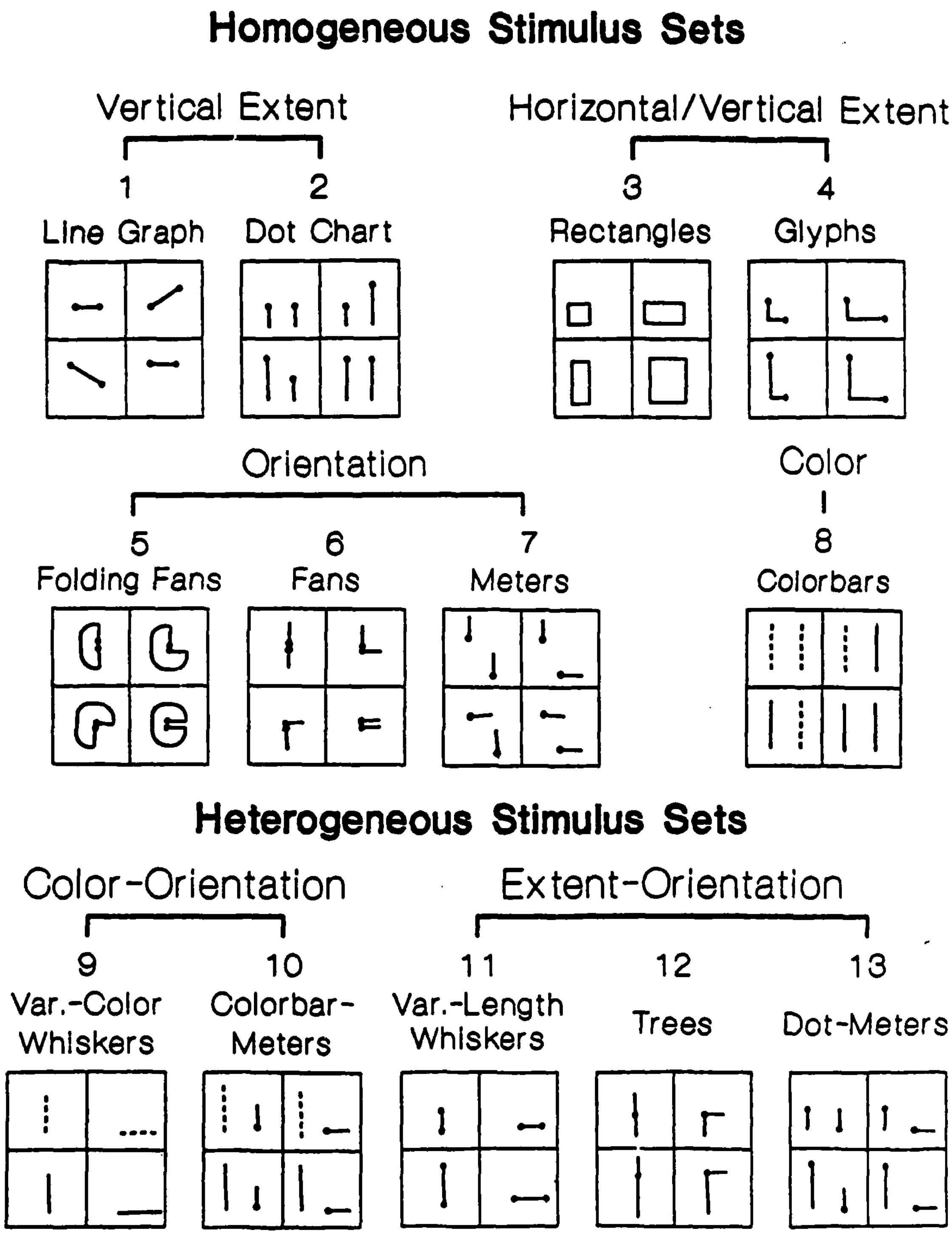


Figure 1. Sample of 13 bivariate graphs, each of which was used by an independent group of subjects to perform nine speeded classification tasks. (The graphs include [1] line graphs, [2] dot charts, [3] rectangles, [4] glyphs, [5] folding fans, [6] fans, [7] meters, [8] colorbars, [9] variable-color whiskers, [10] colorbar-meters, [11] variable-length whiskers, [12] trees, [13] dot-meters.)

homogeneous (repeated) pairings and heterogeneous (nonrepeated) pairings of attributes. This manipulation was chosen based on the research of Garner (1978) linking homogeneity and configurality.

A fourth criterion for inclusion was the resemblance of each graph to a multivariate format actually used in aviation, industry, or statistics. Referring to Figure 1, the line graph and dot chart (Graphs 1 and 2, respectively) represent two of the oldest and most commonly used statistical graphs (see Playfair, 1786, for early examples of "bar charts" and "line charts"). The rectangle display (Graph 3), sometimes known as a "star" display or a "polygon" display when used to represent more than two variables, is a relatively more recent advance in statistical and industrial graphics (e.g., Siegel, Goldwyn, & Friedman, 1971; Woods, Wise, & Hanes, 1981). Likewise, glyphs (Graph 4) are a relatively recent, predominantly statistical innovation (Anderson, 1957). The folding fans, fans, and meters (Graphs 5 through 7, respectively) are variations of semicircular and circular single-pointer and multiple-pointer displays seen in numerous industrial and transportation applications (e.g., analog speedometers, altimeters, tachometers). The colorbars (Graph 8) represent a simplified "bank of color indicators" such as might be seen on a Naval "green board," while the dot-meters (Graph 13) and colorbar-meter (Graph 10) displays represent the separated, heterogeneous multiple indicators typical of many process control work stations (e.g., height of a bar or color of a light to indicate temperature, next to a meter that indicates pressure or other physical variable). Last, the variable-length whiskers (Graph 11), variable-color whiskers (Graph 9), and tree displays (Graph 12) all represent graphical representations with statistical applications (see Chambers, Cleveland, Kleiner, & Tukey, 1983, for a collection of papers describing these and other techniques).

In each row of Figure 1, four variants of each of the 13 graphs are shown. The eight graphical formats illustrated in the left half of the figure are homogeneous, consisting of the same dimension used to display both pieces of information. The five remaining graphs used two different dimensions to communicate information about two variables to subjects.

Eight of the thirteen formats were also classified as singular "object displays" based on previous subjective classification of the stimuli by 20 judges (Carswell, 1988). Five homogeneous displays--the lines, rectangles, glyphs, fans, and folding fans--were classified as single objects. In addition, three heterogeneous displays were designated as object displays--the variable-length whiskers, the variable-color whiskers, and the trees.

Each of the three basic dimensions, regardless of how it was incorporated into a particular graph, was constructed to display two different levels. Therefore, two different line lengths, two different orientations, and two different colors were the essential building blocks of all 13 graphs. In each of the seven graphs that used linear extent as a dimension (i.e., dots, lines, rectangles, glyphs, dots-meters, trees, variable-length whiskers), line lengths of 1.4 centimeters and 2.6 centimeters (cm) were used.

Orientation was used to represent information in eight of the experimental graphs. This group included meters, fans, folding fans, variable-length whiskers, variable-color whiskers, dots-meters, colorbar-meters, and trees. In each of these graphs, either a vertical or horizontal line was used.

Finally, color was used in three of the graphs--the colorbars, the variable-color whiskers, and the colorbar-meters. The colors used in these displays were amber and red, known as "brown" and "dark red" on the IBM® graphics adapter color set. These two colors were described by two raters, each reporting normal color vision, as 4.0 Y 6.5/6 (brown) and 7.5 R 4.5/8 (dark red) using the Munsell color-naming system (Munsell, 1976).

All displays were centered in the middle of a cathode ray tube (CRT) and were surrounded by a brown box. The box measured 5.2 cm by 5.2 cm and subtended a visual angle of approximately 4.29°.

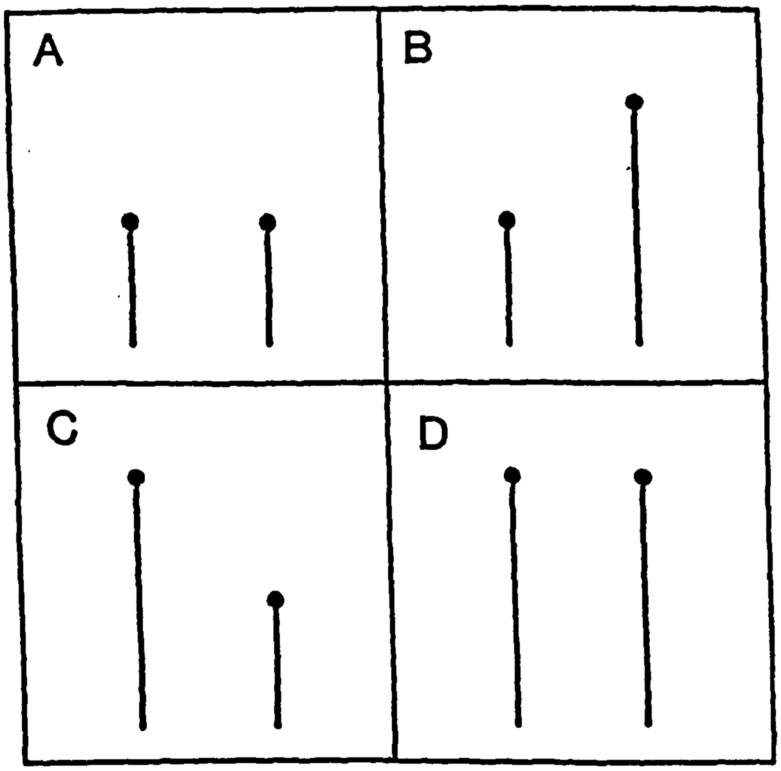
Apparatus

Stimulus presentation and data collection were controlled by an IBM®-PC with a Princeton Graphics HX-12 color monitor and Tecmar Graphics Master graphics board. The monitor and a chair with arm-mounted keypads were positioned inside a darkened booth. The experimenter was positioned outside the booth where two monitors were arranged for viewing, one showing the actual stimuli as they were being presented to the subject, and the other monitor presenting ongoing performance measures.

Tasks

Each subject performed nine different speeded classification tasks with one of the experimental displays (Garner, 1974, 1976; Pomerantz & Pristach, 1989). Figure 2 illustrates the nine tasks using the dot charts as an example. The four quadrants represent the four possible stimuli formed by looking at all possible combinations of two dimensions, each with two levels. For each of the nine tasks, subjects were required to classify or sort a series of stimuli from this set into one of two preestablished categories. The difference between each of the nine tasks depended on the subset of the four stimuli assigned to the categories.

The first four tasks were control tasks used to assess the discriminability of each of the two physical dimensions that were manipulated. In these tasks, only two of the four possible stimuli were included in the series to be sorted, each being sorted into a different category as quickly as possible. In each of these four tasks, only one of the two possible dimensions formally discriminated the two stimuli, the additional dimension was always the same. Referring to Figure 2, the four single dimension baseline tasks involved classifying (1) A versus C, (2) B versus D, (3) A versus B, and (4) C versus D. In the first task, the subject must discriminate the stimuli based on the length of the left line, while the right line or dot remains at the shorter position. In the second task, the subject must once again base the discrimination on the length of the left line, but the right line is fixed at the taller position. Together, the two tasks produce an estimate of baseline discriminability for dimension one, the line length of the left line. The results of tasks 3 and 4 may be used in a similar fashion to determine the discriminability of the right line's length.



Baseline Tasks

(1) A vs. C
(2) B vs. D
(3) A vs. B
(4) C vs. D

Filtering Tasks

(5) (A or B) vs. (C or D)
(6) (A or C) vs. (B or D)

Redundancy Tasks

(7) A vs. D
(8) B vs. C

Condensation Task

(9) (A or D) vs. (B or C)

Figure 2. Nine speeded classification tasks as performed with the dot charts.

Tasks 5 and 6 were filtering tasks that used all four possible stimuli, with two stimuli belonging in each of the two possible classifications. In task 5, for example, Stimuli A and B were sorted against Stimuli C and D. Figure 2 reveals that this classification can be made on the basis of the left line alone, stimuli with short values belonging to one class and those with long line lengths belonging to the other. However, unlike the baseline discrimination trials, the irrelevant line length (right line) does not remain at only one position. Thus, the subject's task is to filter out the irrelevant part of each stimulus, and to sort based on only the left line length. Task 6 pits A and C against B and D, in which case, the left line becomes the irrelevant stimulus and must be ignored.

Tasks 7 and 8 involved sorting stimuli in which the two dimensions varied redundantly. The series of stimuli that subjects were asked to classify, in both cases, contained only two of the possible four stimuli. Task 7 required subjects to sort A versus D, and task 8 required subjects to sort B versus C. For the dot charts (Figure 2), task 7 involved sorting stimuli that were composed of dimensions that varied in a positively correlated manner, while task 8 involved sorting stimuli that were composed of negatively correlated dimensions. In both tasks, either of the dimensions could serve as a sufficient cue for making the classification.

Finally, task 9 was a condensation task in which the correlated subset of stimuli used in task 7 was paired against those used in task 8 for classification. In Figure 2, A and D were sorted against B and C. Unlike any of the previous tasks, a strategy that involved focusing on only one of the two attributes of each stimulus was no longer adequate for classification. Instead, subjects had to rely on both dimensions. A short left line, for example, could belong to either specified classification. However, if it was paired with a short right line, it was sorted into the first class; if it were paired with a tall right line, it was sorted into the second class.

Procedure

All subjects participated in individually administered 2-hour sessions. The sessions were composed of four blocks of trials, one practice block and three blocks during which data were collected. During each block, subjects performed nine trials, each trial corresponding to a different task. Each trial consisted of a series of 40 stimuli to be sorted. The order of trials within blocks was determined randomly for each subject and block.

All trials (stimulus series) were conducted as follows: The experimenter first told the subject which type of trial to expect. As a memory aid, the subject had copies of the four possible stimuli, which were labeled as A, B, C, or D. Thus, the experimenter could instruct the subject to, for example, "press the left key if you see either A or D, and press the right key if you see stimulus B or C." A subject receiving these instructions would be prepared to perform task 9, the condensation task. When the subject indicated he or she was ready, the experimenter started the trial. A stimulus would appear on the monitor for a maximum of 3 seconds. If the subject did not respond in that period of time, a "respond faster" message appeared. If the subject made a response within the 3 seconds, and it was incorrect, an "error" message appeared. If the response was correct, no message appeared and the next stimulus was

displayed 1 second after their response. After no response or error trials, the new stimulus was presented 1 second after the message was terminated. After 40 stimuli had been presented in this fashion, the subject was given performance feedback, including the total percentage correct and the mean correct reaction time (RT). The next trial of the block proceeded in a similar fashion. Subjects were given a rest break between their second and third blocks of trials.

Data Analysis

The mean RT data for each of the 13 experiments were submitted to a two-factor (9 tasks x 3 blocks) repeated measures analysis of variance (ANOVA). Before the analysis, any data points more than three inter-quartile ranges above or below the 75th and 25th percentiles for a given task were eliminated from the data set. Percentage correct data were not analyzed for each experiment. However, a correlational analysis of reaction times and percentage correct was conducted individually for each of the subjects in each experiment. Table 1 presents the median correlations found between reaction time and accuracy, along with their ranges, for each of the 13 experiments. The vast majority of correlations were negative, with quicker reaction times associated with higher percentages of correct responses. Thus, only reaction times were analyzed in depth.

The main effect of task was reliable ($p < .0001$) in all 13 experiments, and there was typically a decrease in reaction times across blocks ($p < .05$). Except for those experiments where a Block x Task interaction was observed, only the results of a series of planned comparisons between different tasks are reported. These comparisons are the following five results that are jointly used to infer integrality, separability, or configurality:

1. Mean performance in tasks 1 and 2 versus performance in task 5 (filtering decrement 1).

2. Mean performance in tasks 3 and 4 versus performance in task 6 (filtering decrement 2).

3. Mean estimated "statistical redundancy advantage" (see below) versus performance in task 7 (redundancy gain 1).

4. Mean estimated "statistical redundancy advantage" (see below) versus performance in task 8 (redundancy gain 2).

5. Mean performance in tasks 5 and 6 versus performance in task 9 (condensation efficiency).

The first and second comparisons assess the filtering decrement incurred when classification was based on dimensions 1 and 2, respectively. Comparisons 3 and 4 evaluate the possibility that a redundancy gain occurred exceeding what would be expected by a model postulating separable dimensions processed in parallel (a "horse race" model). Thus, actual performance in each of the correlation tasks was compared with the faster baseline discriminability (the faster of the task 1 and 2 mean vs. task 3 and 4 mean). This modified baseline, or "estimated statistical advantage" is similar to that suggested by

Biederman and Checkosky (1970) for estimating redundancy gain. Finally, comparison 5 compares the condensation task with the mean of the two filtering tasks, in an effort to assess condensation efficiency.

Table 1

Range and Median Correlation Between Reaction Time and Percentage Correct for Each of the 13 Graphs

Graph	Range	Median Correlation
Lines	-.12 to -.86	-.51
Dots	-.18 to -.54	-.40
Rectangles	-.23 to -.74	-.43
Glyphs	-.22 to -.68	-.47
Folding Fans	-.12 to -.88	-.48
Fans	-.19 to -.69	-.44
Meters	+.25 to -.72	-.33
Colorbars	+.02 to -.62	-.41
Variable-Color Whiskers	-.36 to -.89	-.56
Colorbar-Meters	-.04 to -.91	-.41
Variable-Length Whiskers	-.46 to -.83	-.75
Trees	-.14 to -.81	-.55
Dot-Meters	-.29 to -.87	-.37

The diagnosis of integral dimensions depends on evidence of filtering decrements and redundancy gain, while the diagnosis of separable dimensions relies, predominantly, on evidence of poor condensation with no filtering decrements or redundancy gain. The diagnosis of configurality relies on good condensation performance, with filtering decrements but no redundancy gain (and perhaps an asymmetry of redundancy gain, and between-subject variation on filtering decrements). Because the diagnosis of these various types of dimensional interactions requires joint inferences based on several comparisons, only individual comparisons significant at the $p < .01$ level are reported.

After each of the 13 experiments had been individually analyzed using the classical criteria for integrality, configurality, and separability, an integrative analysis was performed using summary measures from each of the 13 experimental graphs. The method for obtaining these summary measures is outlined in Table 2. The measures include overall discriminability, relative discriminability of the two dimensions, redundancy gain, filtering decrements, asymmetry of redundancy gain, condensation efficiency, and variability of filtering decrements. To study the covariance structure of these variables across the various graphs, a principal components analysis was performed.

Table 2

Summary Variable Used in the Principal Components Analysis of Task Performance Across Graphs

Variable name	Description
Total Discriminability	D1 + D2
Relative Discriminability	/D1 - D2/
Redundancy Gain	.5(Df/R1 + Df/R2)
Redundancy Asymmetry	/(Df/R1 - Df/R2)/
Filtering Decrement	.5(F1/D1 + F2/D2)
Filtering Variability	SD(Filtering Decrement)
Condensation Efficiency	Ds/C

Note. D1 = discriminability RT of dimension 1
D2 = Discriminability RT of dimension 2
Df = faster of D1 and D2
R1 = RT of first redundancy condition
R2 = RT of second redundancy condition
F1 = RT of first filtering condition
F2 = RT of second filtering condition
C = RT for condensation task
Ds = slower of D1 and D2
SD = standard deviation

Results and Discussion

The following summary of the data first reports the results for each of the 13 graphs separately. In a final section, the results of the integrative principal components analysis are presented.

Line Graphs

The first column of Table 3 shows the mean RTs and percentage correct responses for the line graphs in each of the nine tasks. An analysis of the two control conditions (position of left endpoint vs. position of right endpoint) revealed no reliable differences, the mean RTs differing by only 1 millisecond (msec). However, a filtering decrement was observed for both dimensions. When the left endpoint was the classification target and the right endpoint varied orthogonally, reaction time was 405 msec, a 95-msec increase compared to baseline ($F[1,8] = 29.51$, $p < .001$). Likewise, when the right endpoint was the target, orthogonal variation of the left endpoint also resulted in a 95-msec decrease from 309 msec for control classification to 404 msec ($F[1,8] = 22.67$, $p < .001$). Reaction times in the two correlation conditions did not behave as symmetrically as those for the two filtering tasks. The comparison of fastest control performance ($M = 303$ msec) with the first redundancy task resulted in no reliable differences. However, when compared to the second redundancy condition, there

was a redundancy loss of 32 msec ($F[1,8] = 10.95$, $p = .01$). Finally, when condensation performance was compared to mean filtering performance, condensation performance was found to be reliably superior. Mean condensation performance was 362 msec, 43 msec less than for filtering trials.

Table 3

Mean Reaction Times (msec) and Percentage Correct for Each of the Nine Classification Tasks Performed With the Line Graphs and Dot Charts

Task[a]	Line graphs RT (% correct)	Dot charts RT (% correct)
Dimension 1[b], Baseline 1 (A vs. C)	305 (95)	346 (96)
Dimension 1, Baseline 2 (B vs. D)	312 (95)	366 (97)
Dimension 2[c], Baseline 1 (A vs. B)	307 (94)	346 (97)
Dimension 2, Baseline 2 (C vs. D)	314 (94)	357 (96)
Filtering 1, Dimension 1 target (A & B vs. C & D)	405 (92)	373 (96)
Filtering 2, Dimension 2 target (A & C vs. B & D)	404 (91)	363 (96)
Redundancy 1 (A vs. D)	301 (96)	335 (97)
Redundancy 2 (B vs. C)	335 (92)	348 (96)
Condensation (A & D vs. B & C)	362 (90)	425 (93)

[a]Letters refer to the actual stimuli being classified. These stimuli are pictured in Figure 1.
[b]Dimension 1 is the vertical position of the left dot for both the lines and the dot charts.
[c]Dimension 2 is the vertical position of the right dot for both the lines and the dot charts.

To summarize, the use of the line graph resulted in reliable filtering decrements, no redundancy gain (and even redundancy loss in one condition), and relatively good condensation performance. Using the present diagnostics, the positions of the two endpoints of the line graph appear tc be strongly configural. Additional evidence for configurality is derived from the between-subject variation noted in orthogonal interference. In both comparisons of orthogonal interference to appropriate baselines, there were significant Subject x Task interactions (orthogonal interference with left endpoint, $\underline{F}[8,64] = 11.29$, $\underline{p} < .0001$; orthogonal interference with right endpoint, $\underline{F}[8,64] = 3.95$, $\underline{p} = .01$). Thus, some subjects suffered from filtering decrements more than others. Such evidence suggests that subjects may be using different strategies, a possibility that remains consistent with the notion of configural dimensions being "optionally separable."

Dot Charts

The second column of Table 3 shows the means for each of the two dependent variables in each of the nine tasks. A comparison of the two control condition means revealed that there was no reliable difference in time to classify the left dot (357 msec) versus the right dot (351 msec). Nor were there differences between either filtering task and the appropriate controls. Further, when the redundancy conditions were compared to the faster discrimination baseline, no reliable differences were found. Finally, condensation was poorer than filtering performance ($\underline{F}[1,8] = 23.71$, $\underline{p} = .0012$), condensation taking a mean time of 425 msec compared to 368 msec for filtering.

These data present a picture of separable dimensions, with neither redundancy gain nor orthogonal interference being demonstrated. However, this picture is rather puzzling when compared with results of Lockhead and King (1977), who also used pairs of lines, each taking on two values as stimuli. Their findings were suggestive of configurality, with filtering and condensation performance almost comparable to baseline control performance. However, the stimuli used by Lockhead and King (1977) were small and spaced closely together. Although the authors do not give the approximate visual angle subtended by their stimuli, the cards used for sorting were only 6 by 8 cm, and the two lines were 6 mm apart. Estimating that there was approximately 1 foot between the stimulus and subject, the stimulus would only subtend approximately 1^{o}. The present stimulus subtended approximately 2^{o} (the distance between lines) and this difference may be reflected in a loss of configurality effects. Consistent with this position, Pomerantz and Schwaitzberg (1975), using a pair of parentheses as their stimulus dimensions, found a decrease in condensation performance when the parentheses were moved from 1^{o} to 2^{o} apart.

Rectangles

The data from each of the nine classifications performed with the rectangle display are presented in Table 4, column 1. Comparisons between the two control conditions resulted in a marginal difference ($\underline{F}[1,8] = 6.66$, $\underline{p} = .03$) with unidimensional classifications of height (M = 328 msec) being somewhat faster than classifications of width (M = 343 msec). When subjects were directed to focus on height while width varied orthogonally, there was an increase in reaction time of 44 msec ($\underline{F}[1,8] = 37.16$, $\underline{p} = .0003$). When subjects were asked

to focus on width with height varying orthogonally, reaction times were increased by 45 msec ($F[1,8] = 24.46$, $p = .001$). Thus, similar filtering decrements were observed for both dimensions. Neither classification task using redundant dimensions showed a reliable difference from the mean of the faster baseline. Finally, condensation performance ($M = 419$ msec) was reliably worse than reaction times for the filtering tasks ($M = 379$ msec) ($F[1,8] = 27.65$, $p = .0008$).

Table 4

Mean Reaction Times (msec) and Percentage Correct for Each of the Nine Classification Tasks Performed With the Rectangles and Glyphs

Task[a]	Rectangles RT (% correct)	Glyphs RT (% correct)
Dimension 1[b], Baseline 1 (A vs. C)	326 (97)	338 (97)
Dimension 1, Baseline 2 (B vs. D)	330 (96)	349 (98)
Dimension 2[c], Baseline 1 (A vs. B)	339 (95)	353 (96)
Dimension 2, Baseline 2 (C vs. D)	342 (95)	355 (96)
Filtering 1, Dimension 1 target (A & B vs. C & D)	372 (95)	348 (96)
Filtering 2, Dimension 2 target (A & C vs. B & D)	388 (94)	365 (96)
Redundancy 1 (A vs. D)	332 (95)	337 (97)
Redundancy 2 (B vs. C)	325 (95)	348 (97)
Condensation (A & D vs. B & C)	419 (92)	482 (93)

[a]Letters refer to the actual stimuli being classified. These stimuli are pictured in Figure 1.
[b]Dimension 1 is the height of the rectangle or the vertical position of the top dot in the glyph.
[c]Dimension 2 is the width of the rectangle or the horizontal position of the bottom dot in the glyph.

The height and width of rectangles, given the present results, do not appear to be clearly separable. Focusing was disrupted for both height and width discriminations when there was orthogonal variation in the irrelevant dimension. However, these two dimensions do not appear to be integral either, since there was no evidence of redundancy gain. The filtering decrements found in the present experiment are consistent with the findings of Felfoldy (1974), who also studied speeded classifications of rectangle height and width. However, unlike the present results, he obtained a redundancy gain in both of his redundancy tasks. It should be noted, however, that Felfoldy failed to obtain the redundancy gain in one part of his experiment. Other results have implicated configurality rather than integrality for these two physical dimensions. For instance, Weintraub (1971) showed that a set of rectangles varying in a negatively correlated fashion along height and width provided for better performance in an absolute judgment task than did a set that varied in a positively correlated manner. One explanation for such a finding is the presence of a more easily identified emergent feature in one of the two sets.

Glyphs

Column 2 of Table 4 presents the mean RTs and accuracies for each of the nine classification tasks. The only one of the comparisons that resulted in a reliable difference was the comparison of condensation to filtering ($F[1,8] = 399.74$, $p < .0001$). While mean performance during filtering trials was 356 msec, condensation demands slowed performance by 126 msec to 482 msec.

These results indicate relatively separable processing of the two manipulated dimensions. It should be noted that of the four displays varying linear extent or position (i.e., the line graphs, dot charts, rectangles, and glyphs), the glyphs resulted in by far the worst condensation performance.

Folding Fans

The RTs and accuracies for each of the nine classification tasks are displayed in column 1 of Table 5. Comparison of the two control conditions, classifications of the orientation of the top half of the fan versus that of the bottom half, revealed no reliable discrepancies. Filtering decrements, however, were evident for both. When the top half of the fan was the classification target, random positioning of the bottom half of the folding fan resulted in RTs 64 msec longer than baseline ($F[1,8] = 36.93$, $p = .0003$). When the bottom half of the fan was the target, orthogonal variation of the upper half resulted in a decrease of 62 msec ($F[1,8] = 20.55$, $p = .003$).

While the two filtering conditions resulted in quite similar performance outcomes, results of the two redundant variation classifications showed very different patterns. One of the two conditions resulted in a marginally reliable redundancy gain ($F[1,8] = 4.99$, $p = .056$), while the other condition resulted in a reliable redundancy loss ($F[1,8] = 19.41$, $p = .002$). A comparison of condensation performance with filtering performance revealed no differences; condensation performance took only 8 msec longer on the average.

As with the line graph, the present data suggest a strong degree of configurality between the component dimensions used to create the folding fan

display. Filtering decrements without clear indication of redundancy gain, differential performance in formally similar redundancy conditions, and relatively efficient condensation performance, all support a diagnosis of configural interaction.

Fans

The mean RTs and accuracies for each of the nine tasks are presented in Table 5, column 2. The RTs for the two control conditions (orientation of upper vs. lower half) were found to be reliably different ($F[1,8] = 18.10$, $p = .003$). Subjects were able to classify the different orientations of the bottom half more quickly than the top half (343 vs. 350 msec). Attempts to focus on either of the two dimensions when the other was varied orthogonally resulted in decrements to performance. A mean filtering decrement of 52 msec was found for the upper orientation, reaction times increasing from 350 msec to 402 msec ($F[1,8] = 13.11$, $p = .007$). For the bottom half, the decrement was approximately 27 msec, RTs increasing from 343 to 370 msec ($F[1,8] = 9.01$, $p = .017$).

The two redundant variation conditions, as with the folding fans, resulted in different levels of performance relative to the faster baseline. For the first of these two conditions, a marginal redundancy gain of 10 msec was observed ($F[1,8] = 6.83$, $p = .03$). No such gain was found for the other redundancy condition, although there was no evidence of a redundancy loss like that obtained for the folding fans. Finally, a marginal difference between orthogonal interference and condensation was found, with condensation performance resulting in a 35-msec decrement.

A number of the characteristics of the fan display are similar to those of the folding fan, only attenuated. For example, orthogonal interference was present, but to a smaller degree in terms of absolute decrement. Likewise, no clear redundancy gain was evident. Performance in the two redundancy conditions offered somewhat differing results, although they did not show the strongly opposing patterns that characterized redundancy performance for the folding fans. In addition, condensation was only slightly less efficient than with the folding fans. These data suggest a somewhat attenuated degree of configurality. Yet, the two dimensions used in the present display are not clearly separable.

Meters

Table 5 (column 3) presents the data categorized by task type for the meters display. No difference was observed between the classification times for the two dimensions used (upper angle vs. lower angle) when the irrelevant dimension was held constant. Further, no reliable decrement from baseline was found for filtering of either attribute, and there was evidence of neither redundancy gain nor loss in either of the two redundant variation tasks. However, condensation performance showed a steep decline compared to filtering performance (452 msec vs. 343 msec) ($F[1,8] = 144.10$, $p < .0001$).

Table 5

Mean Reaction Times (msec) and Percentage Correct for Each of the Nine Classification Tasks Performed With the Folding Fans, Fans, and Meters

Task[a]	Folding Fans RT(% correct)	Fans RT(% correct)	Meters RT(% correct)
Dimension 1[b], Baseline 1 (A vs. C)	338 (96)	347 (95)	328 (92)
Dimension 1, Baseline 2 (B vs. D)	356 (95)	351 (94)	347 (94)
Dimension 2[c], Baseline 1 (A vs. B)	337 (96)	343 (96)	342 (91)
Dimension 2, Baseline 2 (C vs. D)	343 (94)	343 (96)	336 (92)
Filtering 1, Dimension 1 target (A & B vs. C & D)	412 (92)	402 (92)	339 (94)
Filtering 2, Dimension 2 target (A & C vs. B & D)	405 (92)	370 (94)	348 (93)
Redundancy 1 (A vs. D)	332 (96)	329 (95)	332 (93)
Redundancy 2 (B vs. C)	359 (94)	335 (94)	339 (94)
Condensation (A & D vs. B & C)	417 (91)	421 (89)	452 (87)

[a]Letters refer to the actual stimuli being classified. These stimuli are pictured in Figure 1.
[b]Dimension 1 is the orientation of the upper line segment for all three graphs.
[c]Dimension 2 is the orientation of the lower line segment for all three graphs.

These data indicate the two dimensions were processed in a separable fashion. There was no evidence of orthogonal interference or redundancy gain, and condensation performance was relatively poor.

Colorbars

The RTs and accuracies for each of the nine classification tasks are presented in Table 6. Baseline classifications of the two dimensions (color of

bar on left vs. color of bar on right) showed no reliable differences. A marginal filtering decrement was found for the left colorbar when compared to baseline ($F[1,8] = 6.01$, $p = .04$). Thus, variation in the color of the irrelevant right colorbar resulted in an increase of 44 msec. However, a reliable Task x Block interaction occurred so that the difference between baseline and interference performance decreased across the three blocks, from an initial decrement of 74 msec to 37 msec and finally, during block 3, to only 21 msec. No reliable filtering decrement was found for the right colorbar. A marginal redundancy gain was found for one of the redundant variation conditions ($F[1,8] = 6.51$, $p = .04$), but not for the other. Finally, no main effect was found for the comparison of condensation performance and orthogonal interference.

Several aspects of the present data indicate that the colorbars are configural. They allow for relatively successful condensation performance and, in addition, they show an asymmetry in redundancy performance. However, they do not show a strong degree of orthogonal interference, as would be expected for configural dimensions, and the interference present was attenuated with practice. The present display then demonstrates the efficient condensation performance that is typical for configural attributes, but it does so without the usual cost of filtering decrements. There is even a slight trend toward a redundancy gain as well. This pattern of results is quite similar to the hypothetical "free lunch" interaction of attributes that Garner (1976) has called "optional integral" dimensions.

Variable-Color Whiskers

Column 1 in Table 7 presents the mean RTs and accuracies obtained for each of the nine classification tasks. Analysis of the classification time for color versus that for angle in the control conditions revealed that color required 340 msec to process, while angle only required 301 msec ($F[1,8] = 26.43$, $p = .0009$). When angle was the target and color was orthogonally varied, there was no evidence of interference. However, when color was the target, and angle of the line was varied, color classification was increased by 20 msec ($F[1,8] = 12.72$, $p = .007$). Evidence for redundancy gain was found in neither of the redundant variation conditions, and the RTs for the two conditions were approximately equivalent (differing by 1 msec). Condensation performance, however, was far worse than orthogonal interference, with condensation representing a 193-msec decrement ($F[1,8] = 210.96$, $p < .0001$).

Table 6

Mean Reaction Times (msec) and Percentage Correct for Each of the Nine Classification Tasks Performed With the Colorbars

Task[a]	Colorbars RT (% correct)
Dimension 1[b], Baseline 1 (A vs. C)	354 (95)
Dimension 1, Baseline 2 (B vs. D)	355 (95)
Dimension 2[c], Baseline 1 (A vs. B)	345 (96)
Dimension 2, Baseline 2 (C vs. D)	359 (95)
Filtering 1, Dimension 1 target (A & B vs. C & D)	399 (95)
Filtering 2, Dimension 2 target (A & C vs. B & D)	375 (95)
Redundancy 1 (A vs. D)	333 (95)
Redundancy 2 (B vs. C)	338 (96)
Condensation (A & D vs. B & C)	400 (91)

[a]Letters refer to the actual stimuli being classified. These stimuli are pictured in Figure 1.
[b]Dimension 1 is the color of the left bar.
[c]Dimension 2 is the color of the right bar.

Table 7

Mean Reaction Times (msec) and Percentage Correct for Each of the Nine Classification Tasks Performed With the Variable-Color Whiskers and the Colorbar-Meters

Task[a]	Variable-Color Whiskers RT (% correct)	Colorbar-Meters RT (% correct)
Dimension 1[b], Baseline 1 (A vs. C)	336 (96)	340 (93)
Dimension 1, Baseline 2 (B vs. D)	340 (95)	339 (94)
Dimension 2[c], Baseline 1 (A vs. B)	303 (98)	331 (93)
Dimension 2, Baseline 2 (C vs. D)	300 (98)	334 (92)
Filtering 1, Dimension 1 target (A & B vs. C & D)	358 (94)	341 (93)
Filtering 2, Dimension 2 target (A & C vs. B & D)	302 (98)	338 (93)
Redundancy 1 (A vs. D)	297 (97)	335 (94)
Redundancy 2 (B vs. C)	298 (99)	331 (93)
Condensation (A & D vs. B & C)	524 (90)	625 (86)

[a]Letters refer to the actual stimuli being classified. These stimuli are pictured in Figure 1.
[b]Dimension 1 is the color of the whisker in the variable-color whisker, and is the color of the left bar in the colorbar-meters.
[c]Dimension 2 is the orientation of the whisker in the variable-color whisker, and is the orientation of the right line in the colorbar-meters.

Except for the interference caused by orthogonal variation of angle when color was the target for classification, these data seem to suggest fairly separable processing. The filtering decrement obtained must be carefully scrutinized, however, because a similar effect was previously encountered by Harwood, Wickens, and Kramer (1986) who examined the interaction of color and direction. In the previous study, direction (up vs. down) was found to interfere

with the classification of color (red vs. green), but the reverse was not the case. In the present experiment, orientation (horizontal vs. vertical) was found to interfere with color (red vs. brown), but not vice versa. These data do not clearly fit any of the patterns of results identified by Garner (1976). Asymmetrical separability (or integrality) is assumed to also lead to redundancy gains. No such gains were evident in the present study. Asymmetrical configurality may result in unilateral interference effects, as in the present case; however, no other evidence of configurality was found.

Colorbar-Meters

Table 7 (column 2) presents the RTs and accuracies for the classification tasks when the colorbar-meter display was used. The baseline discriminabilities of the two dimensions, color of the colorbar and the orientation of the meter, showed no reliable differences. There was also no evidence of filtering decrements for either dimension. However, results of the redundant variation condition yielded a marginally reliable redundancy loss in one condition ($\underline{F}[1,8] = 5.27$, $\underline{p} = .05$). This condition required subjects to classify red bars with horizontal meters versus gold bars with vertical meters. The redundancy loss was on the order of 10 msec from the "fastest control" baseline (325 msec). The alternate redundant variation condition showed no reliable loss. Finally, condensation performance was far worse than any other condition, with condensation requirements slowing performance by 285 msec.

Like the variable-color whiskers, the colorbar-meters yielded a pattern of results mainly indicative of separable dimensions. However, as with the variable-color whiskers, one piece of evidence strayed from the normal picture of no interference, redundancy gain, or improved condensation performance. In this case, a marginally reliable redundancy loss was obtained in one of the two redundant variation conditions. Once again, this marginal result would not be remarkable if it were not for the previous evidence from Harwood et al. (1986), who likewise found a redundancy loss when color and position (direction in their case) were covaried. Like their stimuli, there was no difference in baseline discriminability for the two dimensions used. Unlike their stimuli, the present dimensions are physically separated.

Garner (1976) writes that "...as long as we are dealing with purely perceptual effects, (redundancy) interference seems very unreasonable, since redundant dimensions can only increase interstimulus differences." However, he notes that simple response competition might occur in some cases. This is one potential explanation for the present results. However, in other studies using color and form dimensions, redundant response-compatible pairings have been associated with losses. Kahneman and Henik (1981) found that subjects trying to report the color of a word in one location were actually slowed down if the congruent color name appeared in another spatial location. Normally, subjects show redundancy gains when asked to name the color of words that are actually the appropriate name of the color to be detected. It seems that more careful analysis of these redundancy losses, particularly in cases when emergent features are unlikely to intervene, should be undertaken. If the possibility of response conflict can be ruled out, these demonstrations will present a difficult obstacle for our present models of dimensional interaction.

Variable-Length Whiskers

Table 8 (column 1) displays the RTs and accuracies for each of the tasks performed with the variable-length whiskers. When baseline classification times for length and orientation were compared, a significant difference was found with orientation providing the quicker judgments by 28 msec ($F[1,8] = 44.09$, $p = .0002$). In the filtering task, when length was the classification target, interference from variations in orientation resulted in a 43-msec filtering decrement ($F[1,8] = 36.67$, $p = .0003$). For angle classifications, length variations resulted in a 19-msec decrement ($F[1,8] = 11.94$, $p = .0086$). It should be noted that the interference caused by orthogonal variation of orientation was attenuated with practice, being reduced from 54 msec in block 1 to 30 msec in block 3 ($F[2,16] = 3.74$, $p = .046$). Neither redundancy condition provided any evidence for either redundancy gain or loss, and condensation performance was relatively inefficient representing a decrement of 213 msec compared to mean orthogonal interference trials ($F[1,8] = 106.41$, $p < .0001$).

While the redundant variation and condensation comparisons tend to support a separable dimensional relationship, the orthogonal interference data are contradictory. However, it should be noted that this difference is diminished with practice. Thus, there is probably more support for a diagnosis of separable dimensions, but the evidence does not converge perfectly.

Trees

Performance data obtained with tree displays in each of the nine classification tasks are presented in column 2 of Table 8. Comparison of the two baseline classifications of orientation and line length revealed no reliable differences. Evidence for orthogonal interference was obtained in both filtering tasks. When orientation of the branch was the target and line length (trunk height) was varied orthogonally, reaction times were increased by 36 msec ($F[1,8] = 52.58$, $p < .0001$). When height was the target and angle (branch location) was varied orthogonally, there was a mean decrement of 79 msec ($F[1,8] = 29.13$, $p = .0003$). In addition, for one of the two redundant variation conditions there was a reliable redundancy loss of 20 msec ($F[1,8] = 19.42$, $p = .0023$). There was also a main effect for the comparison between orthogonal interference performance and condensation ($F[1,8] = 70.96$, $p < .0001$). This difference favored filtering performance by 139 msec.

Once again a relatively ambiguous pattern of results was obtained that does not fit neatly into the pattern expected for integral, separable, or configural dimensions. A failure of selective attention (filtering decrements) was obtained, which would seem to suggest either integrality or configurality. Asymmetrical redundancy loss was also obtained, which would seem to exclude integrality and leave only configurality. However, condensation was relatively poor. If the interactions associated with the colorbars noted earlier may be called a "free lunch," the present pattern must be considered a "bad lunch": filtering decrements, redundancy loss, and poor condensation all in one display.

Table 8

Mean Reaction Times (msec) and Percentage Correct for Each of the Nine Classification Tasks Performed With the Variable-Length Whiskers, Trees, and Dot-Meters

Task[a]	Variable-Length Whiskers RT(% correct)	Trees RT(% correct)	Dot-Meters RT(% correct)
Dimension 1[b], Baseline 1 (A vs. C)	329 (93)	337 (96)	337 (95)
Dimension 1, Baseline 2 (B vs. D)	336 (96)	327 (97)	338 (95)
Dimension 2[c], Baseline 1 (A vs. B)	311 (96)	323 (97)	342 (94)
Dimension 2, Baseline 2 (C vs. D)	300 (96)	327 (97)	341 (93)
Filtering 1, Dimension 1 target (A & B vs. C & D)	376 (91)	408 (93)	343 (95)
Filtering 2, Dimension 2 target (A & C vs. B & D)	324 (95)	361 (95)	354 (94)
Redundancy 1 (A vs. D)	307 (96)	337 (96)	336 (95)
Redundancy 2 (B vs. C)	306 (96)	306 (97)	348 (94)
Condensation (A & D vs. B & C)	563 (85)	524 (91)	599 (86)

[a]Letters refer to the actual stimuli being classified. These stimuli are pictured in Figure 1.
[b]Dimension 1 is the length of the whisker, the length of the tree trunk, and the length of the left line in the dot-meters.
[c]Dimension 2 is the orientation of the whiskers, the orientation of the tree's branch, and the orientation of the right line in the dot-meters.

Dot-Meters

Table 8 (column 3) presents the RTs and accuracies for the dot-meters display. Of the six contrasts made between different classification tasks, only two showed reliable differences. One of the redundant variation conditions

showed a redundancy loss of 18 msec ($F[1,8] = 12.37$, $p = .0079$), and condensation performance was reliably worse than orthogonal interference by 252 msec ($F[1,8] = 45.89$, $p < .0001$).

In general, these data support the separability of the two dimensions. There is no observable orthogonal interference, condensation performance is relatively poor, and there is no redundancy gain. However, there is a slight redundancy loss in one of the two redundant variation conditions. Again, this may be partly because of response conflict since the stimuli were two lines, each having an orientation and length. The mapping of the relevance of each property to the correct response may have triggered the loss.

Performance Patterns Across Formats

Seven summary measures were created to describe aspects of performance in the nine classification tasks considered particularly relevant to attribute interactions. The seven measures, described in more detail in Table 2, included measures of total baseline discrimination performance, differences between baselines, filtering decrements, condensation efficiency, redundancy gain, asymmetry of redundancy performance, and between-subject variability of filtering performance. To study the covariance structure of these variables, the correlation matrix was derived across the 13 graphical formats and was submitted to a principal components analysis.

If either the concept of integrality or configurality adequately describes the variation in dimensional interactions that occurs across graphs in the present sample, a specific pattern of loadings should be observed on one or more of the derived components. This prediction is an application of "converging operations" (Garner, Hake, & Eriksen, 1956), which specifies that particular concepts, such as configurality, can be best selected or eliminated as an explanation for an experimental result if multiple operations are studied. In the present case, the multiple tasks that subjects performed constitute the multiple operations. The pattern of the performance obtained in the tasks is necessary for accepting or rejecting the proposed concepts of dimensional interaction.

Table 9 presents the unrotated factor pattern for the first two principal components. These two components, with eigenvalues of 3.17 and 2.03 respectively, accounted for 74% of the standardized sample variation. Inspection of the loadings on the first component revealed a cluster of the four variables that are purported to diagnose configurality: condensation efficiency, asymmetrical redundancy performance, filtering decrements, and large between-subject variability in filtering. Further, redundancy gain received a relatively low loading, which, along with the presence of redundancy asymmetries, is critical to distinguish integrality from configurality. Thus, the first component seems to be a general configurality component.

Table 9

Unrotated Factor Pattern for the First Two Principal Components Derived From the Correlation Matrix of the Seven Summary Performance Measures

Summary measure	Factor 1	Factor 2
Filtering variability	.91	.19
Redundancy asymmetry	.91	-.20
Filtering decrements	.89	-.37
Condensation efficiency	.68	.63
Total discriminability	-.18	.85
Redundancy gain	-.13	.74
Relative discriminability	-.44	-.38
Eigenvalues =	3.17	2.03

Baseline unidimensional discriminabilities (i.e., long baseline RTs) loaded most heavily on the second component. In addition, redundancy gain and condensation efficiency were highly weighted. It is unlikely that this component represents integrality because filtering decrements received a negative loading. Further, each of the graphs in the present study showed some evidence of asymmetrical redundancy gain. Rather, it is likely that subjects using graphs that have low unidimensional discriminabilities would try to use any emergent or relational property of the graph as a whole to overcome this handicap. The relative weighting on configurality performance suggests that this redundancy gain was more common in graphs with salient emergent features. Because the loadings on condensation efficiency and redundancy gain may be explained as adaptations to low unidimensional discriminability, the second component will be simply labeled "discriminability."

Scores on the first component are plotted against those on the second component in Figure 3. This plot shows that the line and folding fans are strongly configural while the bar-meter display, the dot-meters display, the variable-length whiskers display, and the variable-color whiskers display are all very nonconfigural. Variation along the second component suggests that the colorbars and fans are associated with slow unidimensional classifications, but both show some redundancy advantage as well as relatively good condensation performance. The lines, trees, and variable-length whiskers, on the other hand, are all associated with relatively fast unidimensional classifications.

Two final analyses were performed to assess the relationship of the derived configurality dimension to (1) display homogeneity and (2) object processing. A point-biserial correlation between homogeneity and configurality revealed a weak, positive relationship ($r = 0.52$, $p < .06$). Thus, homogeneous displays were generally more likely to be configural, further supporting the findings of Garner (1978). No such relationship was found between the status of a graph as a single- versus a dual-object display and the derived configurality component, although single objects were more likely than dual objects to have

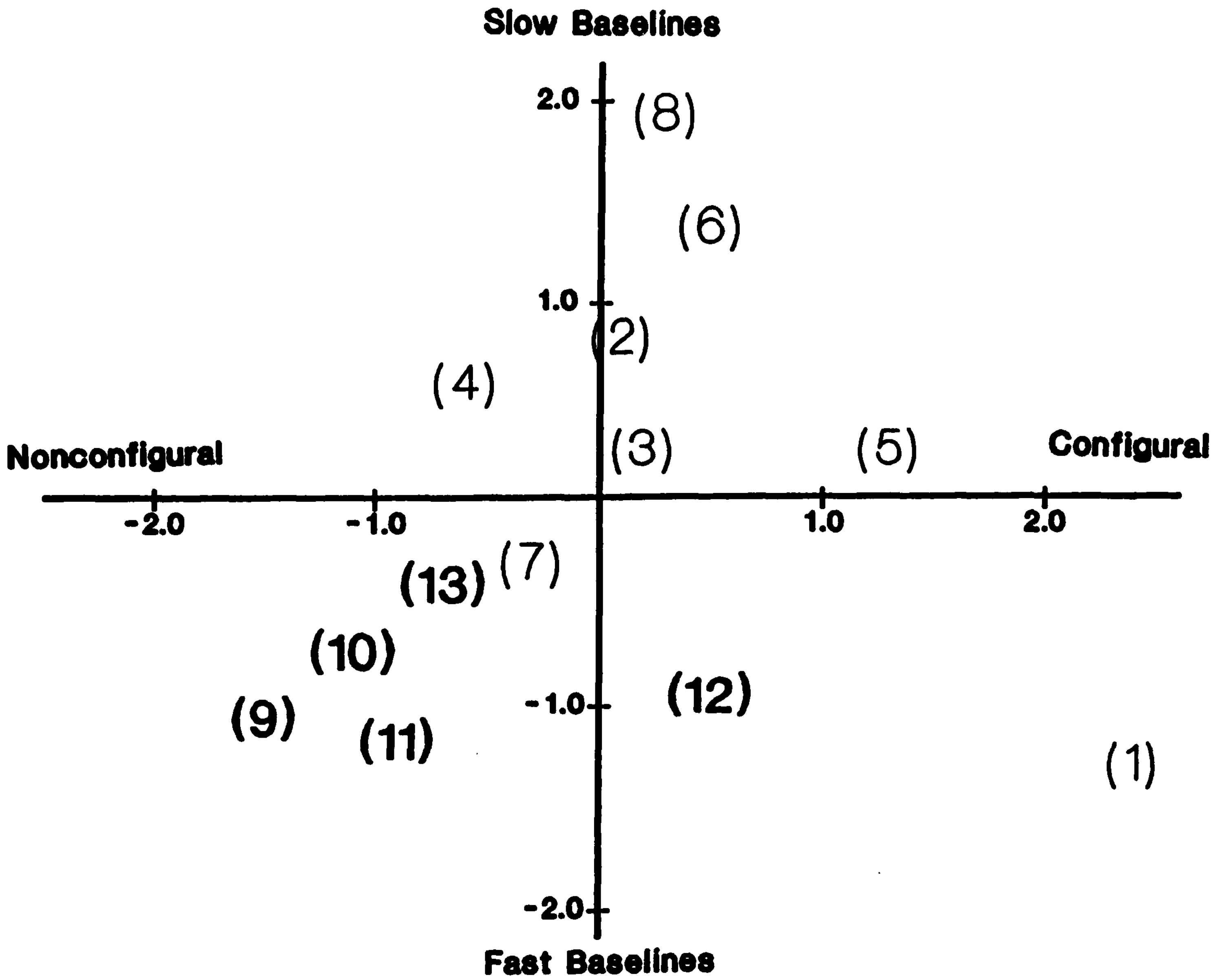


Figure 3. Component scores for the first (horizontal axis) and second (vertical axis) principal components for each of the 13 graphs.

reliable filtering decrements. Seven of the eight object displays showed reliable filtering decrements, the only exception being the glyph. None of the five dual-object displays were associated with filtering decrements.

DISCUSSION

Integrality Versus Configurality

A primary concern of this report was to determine which of the alternate conceptualizations of attribute interaction best characterized a sample of bivariate graphs. Did the majority of these graphs vary along a continuum of configurality, or were the graphs better described as either integral or separable? Using as a diagnostic the pattern of performance in nine speeded classification tasks, 5 of the 13 graphs appeared to be both clearly separable and nonconfigural. For the dot charts, glyphs, meters, colorbar-meters, and dot-meters displays, there was evidence for neither redundancy gain nor filtering loss, and condensation performance was far worse than performance in any other task. Two additional graphs showed performance indicative of separability and low configurality in all respects except for a slight (but reliable) filtering decrement in one of the two filtering tasks. These graphs included the variable-color whiskers and the variable-length whiskers.

Two graphs, the lines and the folding fans, showed strong evidence of attribute interaction. These graphs were associated with filtering decrements and relatively efficient condensation performance. Critically, neither showed redundancy gains, ruling out a diagnosis of integrality. Instead, the pattern fits well with Garner's (1976) description of configurality. In addition, the fan display showed a similar pattern of results, with slightly weaker condensation performance, suggesting an attenuated degree of configurality. An intermediate pattern of results was obtained with both the trees and the rectangle, these graphs being associated with filtering decrements, no redundancy gain, and only moderate levels of condensation efficiency. Neither graph fits into any of Garner's (1976) categories very neatly, although past research of the height and width of rectangles has been suggestive of configurality rather than integrality (Weintraub, 1971). Finally, the colorbars showed an unusual pattern of results including good condensation efficiency with relatively mild filtering decrements, and redundancy gain in one of the two redundancy tasks. This pattern almost suggests a free lunch in terms of performance, with subjects able to divide attention among attributes or focus attention selectively on one or the other, depending on task demands.

These patterns of results have implications for both theories of comparative graphics and for more general theories of attribute interaction. An important aspect of the present data is the absence of any graph associated with the classic integral pattern of task performance--symmetrical redundancy gain with filtering decrements. This suggests that the results of many comparative graphics studies may be influenced more directly by attribute configurality than by integrality. While this assertion depends largely on the extent to which the present graphs are representative of previously studied formats, or those yet to be researched, these data at the very least suggest that configurality should be included as a stimulus variable in research efforts.

In many ways, it is reasonable for graphical displays to consist of configural rather than integral attributes. It seems unlikely that a display designer who was asked to represent some number of variables in a single graph would spontaneously choose dimensions that were not readily analyzable. Thus, the perceptual generative act of creating a graph may bias the choice of dimensions to those that are at least optionally separable (i.e., configural) if not mandatory. This process of choosing display elements should be distinguished from the process of stimulus choice exercised by the scientist wishing to demonstrate the perceptual integrality of specific elements.

Because the choice of the present stimuli was dictated by concerns that they represent common pairings of graphical elements, these results cannot be used as further evidence that "integral dimensions may be a myth" (Cheng & Pachella, 1984, p. 302). However, it should be noted that the alternate conceptualization of dimensional interaction proposed by these authors has some relevance for the present data. Cheng and Pachella (1984) and Pachella et al. (1981) hold that performance with many supposedly integral dimensions can be explained by looking at the degree of correspondence between physical stimuli and psychologically separable dimensions. This proposition predicts "degrees of nonseparabilty," asymmetrical redundancy performance, and redundancy loss, all of which were found in the present experiments. However, this conceptualization seems to overlap greatly with the notion of configural dimensions as an intermediate type of mapping between mandatory integral and separable dimensions. Thus, in essence, Cheng and Pachella argue that many patterns of interaction are better explained by configurality than by integrality, an argument that is consistent within the limits of the present data sample.

By assuming that graphical displays are likely to use configural rather than integral dimensions for variable representation, several inconsistent findings in the comparative graphics literature become interpretable. Casey and Wickens (1986) and Jones, Wickens, and Deutsch (1989) both predicted relatively better performance from an "integral" display when variables were correlated rather than when they were uncorrelated. Instead, these authors found that performance with the integral displays declined with intercorrelation of the variables they represented. If it is assumed that these displays (a "face display" and a polygon, in Casey & Wickens, 1986; and a polygon, in Jones, Wickens, & Deutsch, 1989) were configural, no such advantage would have been predicted. As we have witnessed with several of the displays studied earlier, redundancy loss can sometimes occur with configural displays.

The Measurement of Configurality

If the concept of dimensional configurality is to be a useful one, either to theories of graphical perception specifically or to research of perceptual organization more generally, it is necessary to show that the various operational definitions of the term converge. Analysis of the covariance structure of several scales based on prevalent definitions of configurality and integrality, as well as on measures of attribute discriminability, revealed a relatively straightforward convergence of the configurality measures. The first principal component of the correlation matrix for these measures could be described as a combination of (a) filtering decrements, (b) condensation efficiency, (c)

redundancy asymmetry, and (d) filtering variability. Redundancy gain and unidimensional discriminability, on the other hand, contributed little to this component.

Pomerantz (1981) has previously suggested that condensation efficiency with filtering decrements and without redundancy gain may indicate configurality. In addition, he has suggested that configural displays will show asymmetries between performance in the tasks that require sorting of redundantly paired attributes (Pomerantz & Pristach, 1989). Pomerantz has argued that this is a likely feature of performance with configural attributes because the two types of discriminations may be based on two different emergent features. The present data support the association of redundancy asymmetry with configurality.

Further, a performance outcome that is implied by Garner's definition of configurality as optional separability was also related to the above measures. If configural dimensions allow some degree of strategic processing, between-subject variation in the amount of filtering decrement would be expected. So, those displays which, on the average, tended to show all the signs of high configurality should also be related to large intersubject variability in filtering decrements. This was the case. These results agree with the work of Treisman and Paterson (1984) who showed that there was consistency in the ability of some subjects to use an emergent feature in several different tasks. Within a given task, then, we might expect very different experimental results from those subjects who are able to use such features and those who are not.

Homogeneity of Physical Attributes

The present experiments replicated the work of Garner (1978) which showed that the homogeneity of physical attributes may serve as a correlation of performance-referenced configurality effects. Garner used either brackets or parentheses as attributes, each of which could vary the direction to which it opened (i.e., left opening or right opening). Homogeneous pairings (two brackets or two parentheses) showed stronger configurality effects than did heterogeneous pairings (a bracket with a parenthesis). That is, greater filtering decrements were found for open versus closed judgments of a parenthesis when the to-be-ignored attribute was also a parenthesis. Better condensation performance was also found for such pairs.

In the present experiment, four of the five heterogeneous displays were the least configural of all the displays. The only heterogeneous display that seemed to show some configurality was the tree display. This suggests that homogeneity may serve as one rule of thumb for assessing configurality. However, it should be noted that there was considerable variation among the various homogeneous displays in terms of configurality. One must look for further stimulus characteristics to account for this variation. A possibility, previously studied by Pomerantz and Schwaitzberg (1975) is spatial proximity. For example, the fan display is more configural than the spatially separate meters. Another possibility is similarity of orientation, previously studied for parenthesis pairs by Pomerantz and Garner (1973). Thus, the dots are more configural than the glyphs, which are set at 90° angles to one another, even though the glyphs may be more spatially proximal. It is likely that the importance of physical proximity versus orientation may depend on the homogeneous attributes used.

Object Displays

Finally, the present data may indirectly address some of the conflicting results obtained in studies of single- versus multi-object displays (e.g., Buttigieg et al., 1988; Carswell & Wickens, 1987; Coury & Purcell, 1988). One of the present findings was that object displays were sometimes configural (e.g., line graphs) and sometimes nonconfigural (e.g., variable-length whiskers). Thus, the overall configurality may play an important role in determining when object displays are likely to be used most advantageously. Of the present sample of graphs, the rectangles were the graphs most similar to the "object display" used by Carswell and Wickens (1987) and Buttigieg et al. (1988), as well as to the "configural display" of Coury and Purcell (1988). The dot charts, on the other hand, were representative of the bar charts used in all three experiments. As indicated in Figure 3, both the rectangles and the dot charts were roughly equivalent in terms of their configurality component scores. However, as discussed earlier, it may well be possible to increase or decrease the configurality of graphical elements through proximity or orientation manipulations. Thus, slight differences in arrangements of the bars in a bar graph may result in great differences in terms of its configurality, and may thus explain the discrepancies between the various studies. Buttigieg et al. (1988), for example, have shown that manipulating the mapping of variables to bars in a bar graph results in varying performance advantages for that graph, presumably because of the differential salience and task relevance of the emergent feature(s) produced. Given the organizational variations possible within the basic bar graph format, and given the possible ramifications of these variations on the format's configurality, it is not surprising that Coury and Purcell concluded that the bar graph was "both a configural and a separable display."

Although much remains to be learned about exactly when object displays will provide for enhanced performance, the present data provide some clear-cut evidence for when object displays are likely to be detrimental to performance. For all but one of the object displays in the present sample, subjects were unable to focus attention on one of two varying graphical elements. This was not a problem for any of the multi-object displays. Thus, as recommended by the proximity compatibility principle (Carswell & Wickens, 1987; Wickens & Andre, 1988), object displays should be avoided when focusing on component dimensions is required in the graphical task to be performed.

CONCLUSIONS

The present data suggest that measures of attribute configurality may provide a theoretically useful method of categorizing graphical formats. This conclusion is based on a failure to find one instance of true dimensional integrality in a sample of 13 bivariate graphs. These graphs included object displays and multi-object displays, homogeneous displays and heterogeneous displays, and historically older as well as more recent formats. Although integrality has been used frequently in the literature, configurality may be more appropriate and may more accurately reflect the processing advantages and disadvantages of a variety of graphs.

In addition, several suggested measures of configurality were found to converge in a predicted fashion. An overall configurality score created from the weighted sum of these measures was also found to be related to attribute homogeneity. No strong relationship was found between this composite score and subjective classifications of displays as either single or multiple objects. However, the subjective classification of a graph as a single object display did seem to be related to the difficulty subjects encountered in trying to selectively attend to only one of the graph's attributes. The relevance of these distinctions--object displays and configural displays--to the prediction of graphical efficacy must await further research.

The present results also have considerable potential relevance to the Army's interests in designing efficient interpretable displays in the complex environment typical, for example, of the advanced helicopter. With the abundance of displayed information characteristic of such systems (IEEE, 1987), there is a need to configure that information in a noncluttered format. Integration as an object is one means of reducing this clutter. However, the current results suggest that the physical dimensions chosen for integration may have very different implications for task performance. If they configure, they may support integration, but inhibit the sort of check reading required when operators must evaluate a single variable. If they do not configure, such task-related differences might not emerge. The present results set the stage for three subsequent experiments that have examined the implications of configural and nonconfigural dimensions in somewhat more applied aviation contexts. These will be presented in forthcoming technical reports.

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